

Crust cooling curves of accretion-heated neutron stars

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Abstract: We discuss the recent efforts to use a sub-class of neutron-star X-ray transients (the *quasi-persistent* transients) to probe the properties of neutron-star crusts and cores. Quasi-persistent X-ray transients experience accretion episodes lasting years to decades, instead of the usual weeks to months of ordinary, short-duration transients. These prolonged accretion episodes should significantly heat the crusts of the neutron stars in these systems, bringing the crusts out of thermal equilibrium with their neutron-star cores. When these systems are back in quiescence, i.e. when no more accretion onto the neutron-star surfaces occurs, then the crusts should thermally radiate in X-rays, cooling them down until they are again in thermal equilibrium with the cores. In this chapter we discuss the recent X-ray monitoring campaigns we performed (using the X-ray satellites *Chandra* and *XMM-Newton*) to study several quasi-persistent neutron-star X-ray transients in their quiescent states. These observations gave us, for the first time, a detailed look into the cooling curves of accretion heated neutron-star crusts. In this chapter, we discuss how these crust cooling curves can provide insight into the structure of neutron stars.

1 Introduction

In X-ray binary systems a neutron star or a black hole accretes matter from a nearby companion star, either by Roche-lobe overflow or by wind accretion. Due to conservation of angular momentum the accreted matter does not directly fall onto the compact object, but forms an accretion disk around it. In this accretion disk, angular momentum is transported outward as the matter spirals in. A large amount of gravitational energy (up to $\sim 10^{38}$ erg s $^{-1}$) is released when the matter approaches the compact object, heating the inner accretion disk to very high temperatures ($\sim 10^7$ K) and causing it to emit X-rays. X-ray binaries can be divided into high-mass X-ray binaries and low-mass X-ray binaries (LMXBs) after the mass of the companion star. In the first group the mass of the companion star usually exceeds ten solar masses and the accretion is driven by its strong wind, while in LMXBs the companion's mass is below one solar mass and the accretion is driven by Roche-lobe overflow. Systems which contain a donor star with a mass between one and ten solar

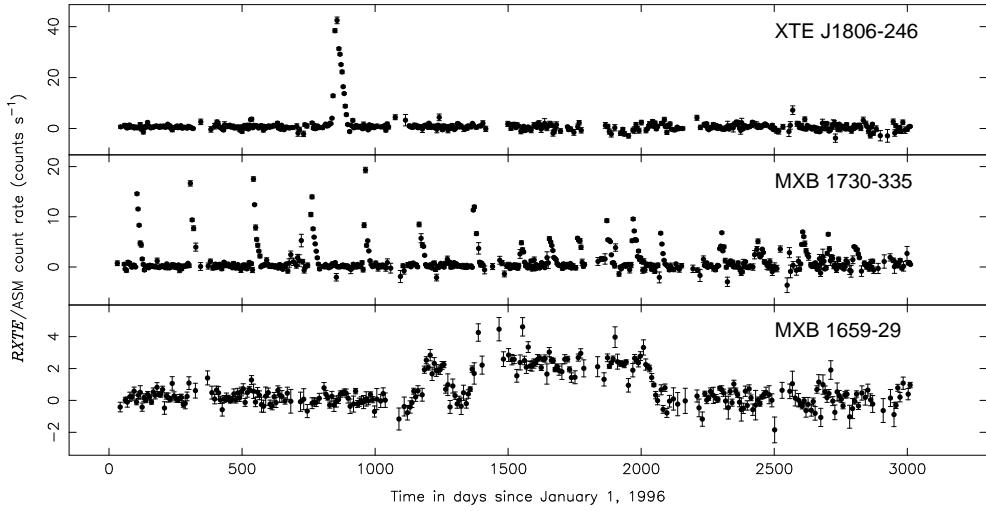


Figure 1: *RXTE*/ASM light curves (since January 1, 1996; i.e., since the start of the *RXTE* mission) of the neutron-star X-ray transients XTE J1806–246 (top), MXB 1730–335 (middle; this source is also known as the Rapid Burster, located in the globular cluster Liller 1), and MXB 1659–29 (bottom). It is clear that a wide variety of outburst durations and frequencies has been observed for different transients. The ASM data points plotted represent four-day averages for XTE J1806–246 and MXB 1730–335, but seven-day averages for MXB 1659–29.

masses are rare, due to the low efficiency of wind accretion and the instability of the mass transfer through Roche-lobe overflow when the donor is more massive than the receiving star. LMXBs can be further classified into *persistent* and *transient* sources depending on their long-term X-ray variability (see § 1.1). A sub-group of the transient sources (the *quasi-persistent* neutron-star X-ray transients) has recently led to advances in our understanding of the properties of the cores and crusts of neutron stars and it is this research that is the focus of this chapter.

1.1 Neutron-star X-ray transients: outburst phase

The neutron-star X-ray transients form a special group among neutron-star LMXBs. They are usually very dim, with luminosities of 10^{32-34} erg s $^{-1}$, but occasionally they exhibit violent outbursts during which their X-ray luminosity increases by several orders of magnitude to 10^{36-38} erg s $^{-1}$ (e.g., Chen *et al.* 1997). These outbursts typically last for several weeks to months before the systems turn off again. For most of these sources only one outburst has been observed, although several have shown multiple outbursts (see Fig. 1 for typical examples of light curves as obtained

with the all sky monitor [ASM] aboard the *Rossi X-ray Timing Explorer [RXTE]* satellite). These outbursts are very likely the result of considerable increases in the mass accretion rates onto the neutron stars in these systems, although the exact physical processes behind these outbursts are still not well understood (see, e.g., Lasota 2001 for a review of outburst physics). Among the transients there is a special sub-class of sources which do not turn off after a few weeks or months but which remain active for many years (the 'quasi-persistent' transients). The best examples of quasi-persistent transients harboring neutron stars are EXO 0748–676 and GS 1826–238 (which are still active), and MXB 1659–29 and KS 1731–260 (which turned off recently). In addition, several neutron-star LMXBs which once were thought to be persistent suddenly turned off (e.g., 4U 2129+47, X1732–304; XB 1905+000; Pietsch *et al.* 1986; Guainazzi *et al.* 1999) and they should also be considered quasi-persistent transients (throughout this chapter when we refer to 'quasi-persistent transients' we mean *quasi-persistent neutron-star X-ray transients* unless otherwise noted¹). During their outbursts, the neutron-star transients (both the ordinary and the quasi-persistent transients) are very similar to persistent neutron-star LMXBs with respect to their X-ray properties and can be readily studied by the X-ray satellites available. However, obtaining high quality X-ray data from the transient systems during their quiescent state still remains a challenge because of the much lower X-ray luminosities.

1.2 Short duration neutron-star X-ray transients: quiescent phase

Despite the low X-ray luminosities of neutron-star X-ray transient during their quiescent state, they can still be detected with sensitive imaging instruments. Although several intrinsically bright and/or nearby systems were already detected with older generation X-ray satellites (e.g., *EXOSAT*, *ROSAT*, *ASCA*, and *BeppoSAX*; van Paradijs *et al.* 1987; Verbunt *et al.* 1994; Garcia 1994; Asai *et al.* 1996, 1998; Campana *et al.* 1998b, 2000; Garcia & Callanan 1999; Stella *et al.* 2000), the launch of the *Chandra* and *XMM-Newton* X-ray satellites with their high sensitivity cameras meant a great leap forward in our ability to detect quiescent systems and to obtain good X-ray spectra (see, e.g., Daigne *et al.* 2002; in 't Zand *et al.* 2001; Rutledge *et al.* 2001a, 2001b; Wijnands *et al.* 2001, 2002b, 2003; Campana *et al.* 2002; Jonker *et al.* 2003, 2004a).

1.2.1 The observed X-ray properties in quiescence

So far, the majority of quiescent neutron-star transients exhibit X-ray spectra that are dominated by a soft (<1 keV) component which can be accurately described by a thermal model such as a black-body model or a modified black-body model like the

¹Note that also quasi-persistent *black-hole* X-ray transients exist, such as GRS 1915+105 (active since May 1992; Paciesas *et al.* 1994) and 4U 1630–47 (active since September 2002; Wijnands *et al.* 2002c), however, we do not discuss these systems in this review.

neutron-star atmosphere (NSA) models. In these NSA models it is assumed that the depth from which the observed photons emerge from the neutron-star atmosphere increases significantly with the energy of the photons, due to the strong dependency of the opacities on energy. Therefore, high energy photons emerge from deeper and hotter layers than less energetic photons. For a particular temperature, the emerging X-ray spectrum is thus harder than the one that would result if the neutron star would radiate as a pure black body. If indeed the neutron star emits a NSA-like spectrum, then fitting that spectrum with a black-body would overestimate the effective temperature (by a factor of 2) and therefore underestimate the emitting area (often by an order of magnitude; see, e.g., Zavlin *et al.* 1996 and references therein).

The NSA models (those assuming a hydrogen atmosphere and a negligible neutron-star magnetic field strength²) have recently dominated the spectral fits reported in the literature of quiescent neutron-star X-ray transients. This is because NSA models provide a clear physical explanation for the shape of the emitted quiescent spectrum and they yield radii of the emitting area which are consistent with the theoretically expected radii of neutron stars. In contrast, black-body models typically give radii which are significantly lower than those expected for neutron stars. However, it is important to stress that black-body models provide fits to the data that are equally as satisfying as those of NSA models. Thus, currently, we cannot distinguish between these models observationally.

When fitting NSA models to the X-ray spectra of most quiescent neutron-star transients, we observe that they have typically an effective temperature (all effective temperatures in this chapter are for an observer at infinity) of 0.1–0.2 keV and a bolometric luminosity between 10^{32} and 10^{34} ergs s^{−1}. Several systems have been found to exhibit an additional spectral component which dominates the spectrum above a few keV and which can be described by a simple power-law model (e.g., Asai *et al.* 1998; Rutledge *et al.* 2001a, 2001b). This component can contribute up to 50% to the 0.5–10 keV quiescent flux of a particular system (e.g., Rutledge *et al.* 2001b), although in other systems it cannot be detected and at most 10%–20% of the 0.5–10 keV flux might be due to such an additional hard spectral component (e.g., Wijnands *et al.* 2003).

Although most systems are dominated by the soft thermal component, two systems are known *not* to follow this general trend. Instead, they are dominated by the hard power-law component (contributing >90% to the 0.5–10 keV quiescent flux) and no thermal component could be conclusively detected. Campana *et al.* (2002) found that the accretion-driven millisecond X-ray pulsar and X-ray transient SAX J1808.4–3658 had a quiescent spectrum which was dominated by the hard power-law component. Furthermore, its quiescent luminosity was observed to be 5×10^{31}

²The neutron stars in X-ray transients are assumed to have magnetic field strengths of only 10^8 – 10^9 Gauss, which is sufficiently low not to affect the spectra emerging from the neutron star. Thus the appropriate NSA models are those which assume a zero magnetic field strength.

ergs s⁻¹, which makes it the (intrinsically) faintest quiescent neutron-star transient currently known. Very recently, Wijnands *et al.* (2004b) found that, EXO 1745–248 in the globular cluster Terzan 5, is the second system with a quiescent X-ray spectrum dominated by the hard power-law component. Again the thermal component could not be detected and it contributed at most 10% to the quiescent 0.5–10 keV flux. Although this resembles SAX J1808.4–3658, the 0.5–10 keV luminosity of EXO 1745–248 was a factor of 40 larger than that observed for SAX J1808.4–3658. Currently, it is not understood why SAX J1808.4–3658 and EXO 1745–248 are different from the majority of quiescent neutron-star X-ray transients.

1.2.2 Theoretical models for quiescent neutron-star X-ray transients

Several theoretical models have been developed to explain the low quiescent X-ray luminosities and the X-ray spectra observed for neutron-star X-ray transients. For example, the X-rays could be due to the residual accretion of matter onto the neutron-star surface or down to the magnetospheric boundary, or the pulsar emission mechanism might be active (see, e.g., Stella *et al.* 1994; Zampieri *et al.* 1995; Corbet 1996; Campana *et al.* 1998a; Menou *et al.* 1999; Campana & Stella 2000; Menou & McClintock 2001). The model currently most often used to explain the soft component is the 'cooling neutron star model'.

In this model (e.g., Campana *et al.* 1998a; Brown *et al.* 1998) the radiation emitted below a few keV is thermal emission originating from the neutron star surface. Brown *et al.* (1998) argued that the neutron star core is heated by the nuclear reactions occurring deep in the crust when the star is accreting. This heat is released as thermal emission during quiescence. If the quiescent emission is dominated by the thermal emission of the cooling neutron star, then the quiescent luminosity should depend on the time averaged (over 10^{4–5} years) accretion luminosity of the system (Campana *et al.* 1998a; Brown *et al.* 1998). Thus, the quiescent luminosities observed can be directly compared with luminosities predicted using estimations of the long term accretion history of the sources.

The version of the cooling neutron star model presented by Brown *et al.* (1998) was able to explain, at the time of its publication, the luminosities of most of the systems then detected, although it was found that the neutron-star transient Cen X-4 appeared to be less luminous than this model predicted. This could be due to an overestimation of the time-averaged accretion rate of Cen X-4 or due to the existence of enhanced cooling processes in the core of the neutron star (e.g., due to the direct Urca process, pion condensation, or Cooper-pairing neutrino emission) instead of the standard core cooling processes assumed by Brown *et al.* (1998). Since the publication of the Brown *et al.* (1998) paper, *Chandra* and *XMM-Newton* have provided us with high quality data on about a dozen quiescent neutron-star systems. We now know that Cen X-4 is not the only system which is colder than expected on the basis of its time-averaged accretion history and the standard cooling model (e.g., Campana *et al.* 2002; Nowak *et al.* 2002). It seems that two groups of sources

exist: those which can be explained by assuming standard core cooling and those which require enhanced core cooling processes.

Not all characteristics of the quiescent emission can be fully explained by the cooling neutron star model (either using standard or enhanced core cooling). For example, the neutron-star transients Aql X-1, Cen X-4, and SAX J1748.9–2021 (located in the globular cluster NGC 6440) have shown considerable variability in their quiescent properties on time scales ranging from hundreds of seconds to years (Rutledge *et al.* 2002a; Campana & Stella 2003; Campana *et al.* 2004; Cackett *et al.* 2004). This variability cannot easily be explained by a cooling neutron star and extra ingredients need to be added to the cooling model (e.g., Ushomirsky & Rutledge 2001; Brown *et al.* 2002) or alternative models must be used to explain the quiescent properties (e.g., Campana & Stella 2003; Campana *et al.* 2004). Furthermore, the power-law shaped spectral component which dominates the quiescent spectra above a few keV in several systems cannot be explained by the cooling models. The difficulty is even more dire when attempting to explain the hard, power-law component that dominates the quiescent X-ray spectra of SAX J1808.4–3658 and EXO 1748–248. It is conceivable that this component might be described by one or more of the alternative models mentioned above (i.e., those which assume that the neutron star has a non-negligible magnetic field strength). However, the observational results on this component and our understanding of its nature are very limited.

2 Quasi-persistent neutron-star transients in quiescence

Recently, we have demonstrated that quasi-persistent neutron-star X-ray transients provide an excellent opportunity to improve our understanding of the emission mechanisms at work in quiescent neutron-star systems as well as elucidating the response of neutron-stars to prolonged accretion periods (Wijnands *et al.* 2001; Rutledge *et al.* 2002b). If the long durations of the accretion episodes for these sources are typical (every outburst lasts similarly long) and they are in quiescence for only decades (similar to short-duration transients), then the cooling model predicts that the cores of neutron stars in quasi-persistent systems should be heated to considerably higher temperatures than those of the short-duration transients, and consequently they should be more luminous (factor of >10) in quiescence. This situation is further complicated because the prolonged accretion has a considerable effect on the crust (Rutledge *et al.* 2002b; for ordinary transients the effect is much less). The crust will also be heated to very high temperatures during the outburst and, depending on the crustal relaxation time to return to thermal equilibrium with the core after the outburst, the luminosity and temperature obtained for these systems should reflect those of the crust and not of the core. The exact crust relaxation time is unknown and estimates range from years to decades. Monitoring observations of quasi-persistent systems in their quiescent state following one of their prolonged

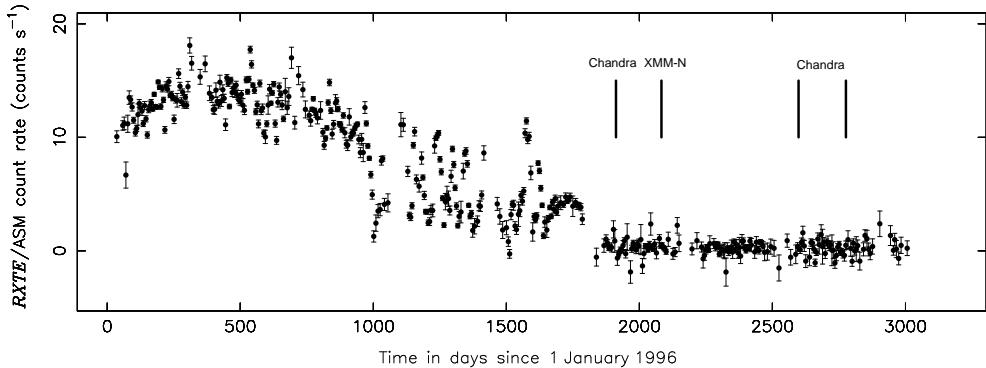


Figure 2: The *RXTE*/ASM light curve of KS 1731–260 since January 1, 1996. The beginning of the outburst was not observed since the source first became active in 1989, more than 6 years before the launch of *RXTE*. The four solid lines show where our *Chandra* and *XMM-Newton* observations were taken. The ASM data points are 5-day averages.

accretion events may allow for a determination of the structure of neutron stars by comparing the observed cooling curves with those calculated (e.g., Rutledge *et al.* 2002b). Recently, we have used two quasi-persistent neutron-star transients (KS 1731–260 and MXB 1659–29) in quiescence to constrain neutron-star cooling curves and the structure of neutron stars. Furthermore, at the time of writing this chapter (April 2004), several other quasi-persistent neutron-star X-ray transients have also been observed in quiescence. Below, we discuss all quasi-persistent neutron-star systems observed, paying particular attention to KS 1731–260 and MXB 1659–29.

2.1 KS 1731–260

KS 1731–260 was first discovered in August 1989 using the *Mir*/Kvant instrument (Sunyaev 1989). The compact object in this new transient was proven to be a neutron star based on the detection of several type-I X-ray bursts³ (Sunyaev 1989; Sunyaev *et al.* 1990). Since its initial discovery, the source was observed as a persistent source (Yamauchi & Koyama 1990; Barret *et al.* 1992, 1998; Smith *et al.* 1997; Wijnands & van der Klis 1997; Munoz *et al.* 2000; Narita *et al.* 2001) until the end of 2000 or early 2001 when it suddenly turned off after having actively accreted for over 12.5 years (Fig. 2). A *Chandra* observation taken a few months after this transition (Fig. 2) showed the source at a bolometric luminosity of a few times 10^{33} erg s^{−1} (Wijnands *et al.* 2001, 2004c). Assuming that the long active period of KS

³Type-I X-ray bursts are thermonuclear explosions on the surface of accreting neutron stars. Since a surface is needed to produce these bursts, observing this phenomenon from a particular accreting system immediately rules out a black hole in favor of a neutron star.

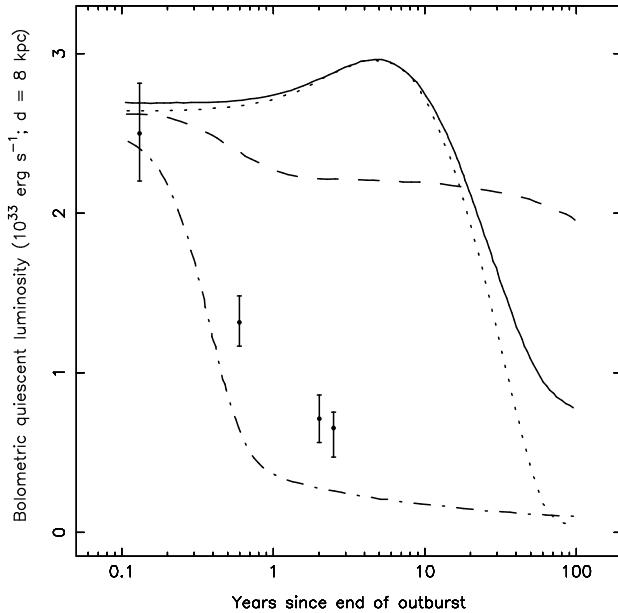


Figure 3: The cooling curves for KS 1731–260 calculated by Rutledge *et al.* (2002b). The solid line and dotted line assume low crustal conductivity with standard or enhanced core cooling, respectively. The dashed and dash-dotted lines correspond to large crustal conductivity and standard or enhanced core cooling, respectively. The luminosity measurements are given in the figure, although normalized so that the first data point is consistent with the cooling curves. The luminosity data points were obtained by fitting a NSA model (the hydrogen NSA model for weakly magnetized neutron stars of Zavlin *et al.* 1996) to the spectral data. The data points are still preliminary and the full detailed analysis will be published by Wijnands *et al.* (2004c).

1731–260 is typical for this source, the standard cooling model predicts that the neutron-star core should be rather hot compared to that of ordinary, short-duration transients, thus appearing as a very bright quiescent system (as explained above). Furthermore, the long active period would have heated the crust to high temperatures (Rutledge *et al.* 2002b; much hotter than the core), which should make the system even brighter. However, the low luminosity observed with *Chandra* is very similar to what has been observed for the short-duration systems in their quiescent states. Thus, the neutron-star crust and core in KS 1731–260 were considerably colder than predicted by the standard cooling model. Several scenarios could explain the unexpected faintness of this source (Wijnands *et al.* 2001). First, it may be that the recent accretion history of KS 1731–260 is atypical and instead this source

usually spends nearly a thousand years in quiescence between outbursts (such long quiescent intervals are not expected in the models proposed to explain X-ray outbursts; e.g. Lasota 2001). Second, and more likely, it may be that the core of the neutron star in this system undergoes enhanced cooling. This would allow for the star to cool down quickly, making it very cold prior to the last outburst episode. Then, during the outburst, the crust is only heated to the observed temperature. Based on this first quiescent observation of KS 1731–260, Rutledge *et al.* (2002b) calculated four cooling curves for the neutron star in this system, assuming different microphysics for the core (standard vs. enhanced core cooling) and the crust (a large vs. small heat conductivity; the heat conductivity depends on the purity of the crust, with a large conductivity when the crust is a pure crystal).

To follow the cooling of the neutron star (i.e., its crust) and to test the calculated cooling curves of Rutledge *et al.* (2002b), KS 1731–260 was observed three more times, once with *XMM-Newton* in 2001 (Wijnands *et al.* 2002b) and twice in 2003 using *Chandra* (Wijnands *et al.* 2004c; Fig. 2). The *XMM-Newton* observation found that the source had decreased in luminosity within half a year by a factor of $\sim 2\text{--}3$. This indicated that the crust had cooled down further, which is consistent with the observed decrease in the effective temperature (from 0.11 to 0.09 keV). During a preliminary analysis (the details of the analysis will be published by Wijnands *et al.* 2004c) of the additional two *Chandra* observations, we found that the source had decreased considerably (factor ~ 8) in count rate compared to the first observation (Fig. 3). We fitted the obtained spectra using a hydrogen NSA model (for weakly magnetized neutron stars; Zavlin *et al.* 1996) to determine how the bolometric luminosity and its associated effective temperature decreased in time. We found that the bolometric luminosity dropped from 3×10^{33} erg s $^{-1}$ to 0.8×10^{33} erg s $^{-1}$ in ~ 2.5 years (Fig. 3) and the effective temperature decreased from 0.11 keV to 0.08 keV. In the cooling model, this decrease in luminosity means that the crust has cooled down significantly over time. When comparing the results with the cooling curves constructed for KS 1731–260 (Rutledge *et al.* 2002b; Fig. 3) it is clear that none of these curves fit the data. However, the curves have large uncertainties in their normalizations and in their exact shapes due to the uncertainties in accretion history and neutron-star properties (Rutledge *et al.* 2002b). The curve which fits the data points best is the one which assumes a large crustal heat conductivity and the presence of enhanced core cooling processes. In addition, we see a possible leveling off of the luminosity of KS 1731–260, indicating that the crust may soon come into thermal equilibrium with the core and further observations of this source in its quiescent state may yield the state of the core of its neutron star. More detailed cooling curves must be calculated for the neutron star in KS 1731–260 to determine if the cooling model can fully explain the observations.

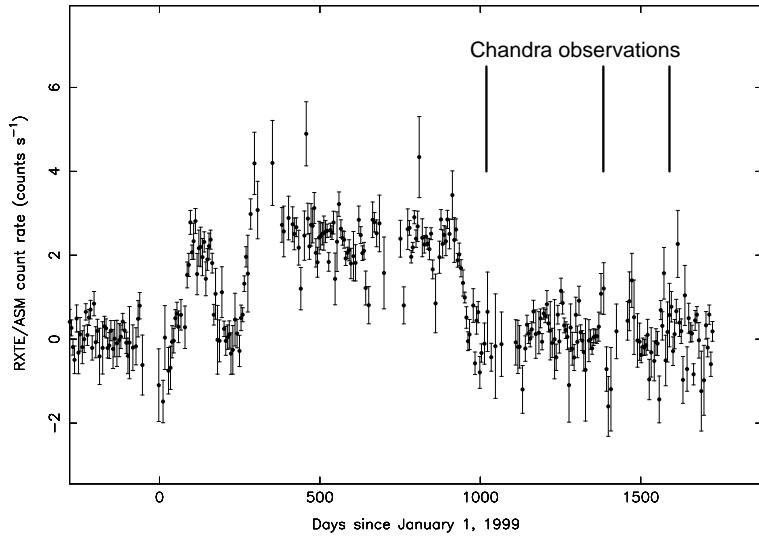


Figure 4: The *RXTE*/ASM light curve of MXB 1659–29 clearly showing the 1999–2001 outburst. The times of the *Chandra* observations are indicated by the solid lines. All *Chandra* observations were performed at times when the *RXTE*/ASM could not detect the source. The ASM data points are 7-day averages.

2.2 MXB 1659–29

MXB 1659–29 was discovered in 1976 by Lewin *et al.* (1976) during type-I X-ray bursts, which clearly established the compact object in this system as a neutron star. The source was detected several times between October 1976 and September 1978 with *SAS3* and *HEAO* (e.g., Lewin *et al.* 1978; Share *et al.* 1978; Griffiths *et al.* 1978; Cominsky *et al.* 1983; Cominsky & Wood 1984, 1989). At that time the source remained active for ~ 2.5 years (see Wijnands *et al.* 2003). Pointed *ROSAT* observations in the early 1990’s failed to detect the source in its quiescent state with an upper limit on the 0.5–10 keV flux of $(1 - 2) \times 10^{-14}$ erg cm $^{-2}$ s $^{-1}$ (Verbunt 2001; Oosterbroek *et al.* 2001; Wijnands 2002).

MXB 1659–29 remained dormant until April 1999, when in ’t Zand *et al.* (1999) reported it to be active again in observations obtained with the *BeppoSAX* Wide Field Camera (see Figs. 1 and 4). The source was observed on several occasions during this outburst using *BeppoSAX*, *RXTE*, and *XMM-Newton* (e.g., Wachter *et al.* 2000; Oosterbroek *et al.* 2001; Sidoli *et al.* 2001). The source remained bright for almost 2.5 years before it became quiescent again in September 2001 (Fig. 4). Because of its long outburst durations, MXB 1659–29 can be classified as a quasi-persistent source. It is interesting to note that the outburst episode in 1999–2001 was similar in length to the outburst episode in 1976–1978 which would suggest that such long outburst durations are a common property of MXB 1659–29 (see

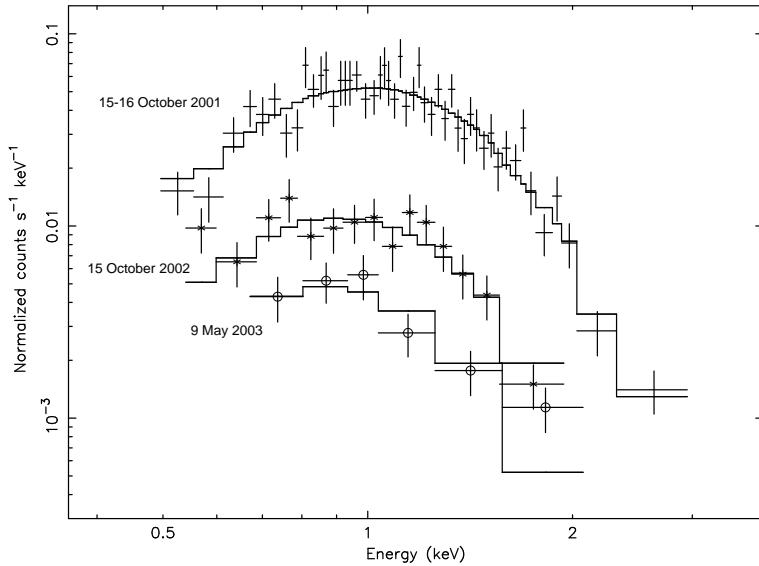


Figure 5: The *Chandra* X-ray spectra obtained during the quiescent state of MXB 1659–29. The top spectrum was obtained on October 15–16, 2001, the middle spectrum (indicated by the crosses) was obtained on October 15, 2002, and the bottom spectrum (indicated by the open circles) was obtained on May 9, 2003. The solid lines through the spectra indicate the best fit neutron-star hydrogen atmosphere model (the one for weakly magnetized neutron stars of Zavlin *et al.* 1996).

Wijnands *et al.* 2003 for a discussion).

A month after MXB 1659–29 turned off in 2001 we observed it using *Chandra* (Fig. 4) and we found a thermal spectrum with an effective temperature of 0.12 keV and a bolometric luminosity of 5×10^{33} erg s⁻¹ (Wijnands *et al.* 2003). These properties are again very similar to those of ordinary quiescent neutron-star systems despite the prolonged accretion episode which would require the neutron-star crust, which should be considerably out of thermal equilibrium with the core, to dominate the X-ray emission observed. Further monitoring observations of MXB 1659–29 were performed in 2002 and 2003 (Wijnands *et al.* 2004a; Fig. 4). Again the spectra of the source were consistent with thermal radiation from the neutron-star surface (Fig. 5). The bolometric flux decreased by a factor of 7–9 over the span of 1.5 years (Fig. 6) and the rate of decrease followed an exponential decay function. Furthermore, the effective temperature also decreased and the rate of decrease again followed an exponential decay function. We found that the *e*-folding time of the effective temperature curve was consistent with four times that of the bolometric flux curve, as expected if the emission is caused by a cooling black body for which the bolometric luminosity is given by $L_{\text{bol}} = 4\pi\sigma R_{\infty}^2 T_{\text{eff}}^{\infty 4}$ (with T_{eff}^{∞} the effective

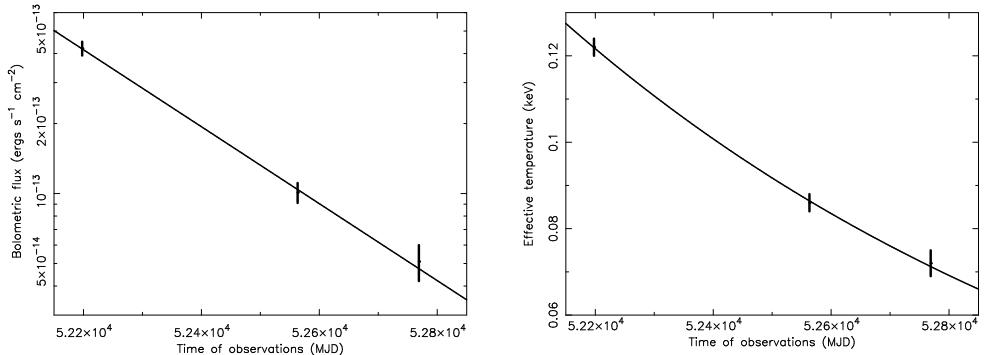


Figure 6: The bolometric flux (left) and effective temperature (right; for an observer at infinity) of the neutron-star crust as a function of time (as obtained with the neutron-star hydrogen atmosphere model for weakly magnetized neutron stars of Zavlin *et al.* 1996). The solid curves are the best fit exponential function through the data points. The bolometric fluxes are plotted on a logarithmic scale, but for clarity, the effective temperatures are plotted on a linear scale.

temperature for an observer at infinity and L_{bol} the bolometric luminosity of the source). This is consistent with the hypothesis that the observations correspond to a cooling crust which was heated considerably during the prolonged accretion event and which is still out of thermal equilibrium with the core.

The cooling curves for the neutron star in KS 1731–260 (Rutledge *et al.* 2002b) can be used as a starting point to investigate how the results observed for MXB 1659–29 could be explained. Of those curves, only the one which assumes a large crustal conductivity and the presence of enhanced core cooling processes exhibits a large luminosity decrease in the first two years after the end of the last outburst, suggesting that the neutron star in MXB 1659–29 has similar properties. But detailed cooling curves for the neutron star in MXB 1659–29 need to be calculated to fully explore the impact of these *Chandra* observations on our understanding of the structure of neutron stars. The cooling curves calculated by Rutledge *et al.* (2002b) for KS 1731–260 only give us a hint of the behavior of MXB 1659–29 because they depend on the long-term ($>10^4$ years) accretion history of the source. For KS 1731–260, this long-term accretion behavior was quite unconstrained due to large uncertainties in the averaged duration of the outbursts, the time-averaged accretion rate during the outbursts, and the time the source spent in quiescence. However, the accretion history of MXB 1659–29 over the last three decades is much better constrained (Wijnands *et al.* 2003), which will help to reduce the uncertainties in its long-term averaged accretion history allowing for more detailed cooling curves to be calculated for MXB 1659–29. This might help to constrain the physics of the crust better for MXB 1659–29 than for KS 1731–260.

The 0.5–10 keV flux during the last *Chandra* observation remained higher than the upper limit found with *ROSAT* (Verbunt 2001; Oosterbroek *et al.* 2001; Wijnands 2002), suggesting that the crust will cool even further in quiescence and that the crust and core have not yet reached thermal equilibrium. Further monitoring observations are needed to follow the cooling curve of the crust to determine the moment when the crust is thermally relaxed again. When this occurs, no significant further decrease of the quiescent luminosity is expected and from this bottom level the state of the core can be inferred. As of yet, we have found no evidence that the flux and temperature are reaching a leveling-off value (Wijnands *et al.* 2004a), associated with the temperature of the core, although the limits we obtained are not very stringent.

2.3 Alternative models

Our observations of KS 1731–260 and MXB 1659–29 demonstrated that quasi-persistent sources can set tight constraints on the structure of neutron stars. It is important to note that this assumes that the observed properties are indeed due to a cooling crust and not due to some other process. Alternative models (e.g., residual accretion or the onset of the radio pulsar mechanism; Campana *et al.* 1998a, Campana & Stella 2000) for the quiescent emission of KS 1731–260 have been proposed (e.g., Burderi *et al.* 2002). Similarly, Jonker *et al.* (2004a) suggested that the difference in the luminosity of MXB 1659–29 between the *ROSAT* non-detection and the 2001 *Chandra* observation might be due to differences in residual accretion rate onto the surface (residual accretion could indeed produce soft spectra; e.g., Zampieri *et al.* 1995). However, these models are far less predictive and thus less verifiable than the cooling model. On the other hand, unlike the cooling model, those alternative models predict that KS 1731–260 and MXB 1659–29 should be similar to other systems if their neutron-star parameters (i.e., spin rates and magnetic field properties) are similar. However, the most recent results on KS 1731–260 and MXB 1659–29 (Figs. 3 and 6) might pose extra problems for the alternative models for the quiescent emission of both systems. Although the variations in bolometric luminosities for both sources can in principle be explained by assuming variability in the accretion rate or the amount of matter which interacts with the magnetic field, the exponential decay curves we observe for the bolometric luminosities and effective temperatures indicate that these alternative processes must also decrease exponentially with a timescale of \sim 1–2 years. Although this cannot be completely ruled out, we believe it is unlikely since short-duration neutron-star transients have been observed to reach their quiescent states on time-scales of tens to several tens of days at the end of their outbursts (e.g., Aql X-1: Campana *et al.* 1998b; RX J170930.2–263927; Jonker *et al.* 2003⁴) and the variations in accretion rate tend to

⁴Recently, we became aware of the results of an additional *Chandra* observation of RX J170930.2–263927 which was performed \sim 14 months after the last *Chandra* observation reported in Jonker *et*

be more stochastic. Moreover, if the neutron stars have significant magnetic field strengths, then this might inhibit any material from reaching the neutron-star surfaces when accreting at the inferred low accretion rates. Despite this, alternative models should be considered when interpreting the results obtained. Further monitoring observations of both sources could rule out some models completely. In the cooling model, large variations in the quiescent luminosities are not expected anymore. If such large variations are observed then this would require an alternative explanation for the quiescent emission. In particular, large increases in luminosity might indeed be caused by a sudden surge in the accretion rate.

2.4 Other sources

Several quasi-persistent neutron-star X-ray transients have been observed in quiescence in addition to KS 1731–260 and MXB 1659–29. Unfortunately, those additional sources do not provide useful constraints on the properties of the neutron-star crust and core. This is because the observations were taken years after the end of the last prolonged outburst episodes, the outburst histories (and thus the accretion histories) of those sources are not well known, and the data are of insufficient quality to constrain the X-ray spectra (and sometimes even the bolometric luminosities). Below, I discuss briefly these additional sources.

2.4.1 EXO 0748–676

This source was discovered with *EXOSAT* in February 1985 (Parmar *et al.* 1986). Since then it has consistently been detected at relatively high luminosities ($> 10^{36}$ erg s $^{-1}$), and therefore, this source can be regarded as a quasi-persistent transient which has been active now for nearly 20 years. Before its discovery, the source had been serendipitously observed with *EINSTEIN* in May 1980 at a quiescent luminosity of $\sim 10^{34}$ erg s $^{-1}$ (Parmar *et al.* 1986; Garcia & Callanan 1999). Usually, this high quiescent luminosity is explained as due to a relatively high level of residual accretion during this particular observation (see, e.g., Garcia & Callanan 1999). However, if EXO 0748–676 is typically active *and* quiescent for a few decades at a time, then from the Brown *et al.* (1998) model (and assuming standard core cooling and that the long duration of the outburst episodes are typical for the source), we would expect it to have a quiescent luminosity of 10^{34-35} erg s $^{-1}$, consistent with what has been observed (see also Wijnands 2002). So, even though KS 1731–260 does not behave as the simplest version of the Brown *et al.* (1998) model predicts, EXO 0748–676 might still do. *Chandra* or *XMM-Newton* observations are needed to

al. (2003). During this new observation the source had a quiescent luminosity (P. Jonker private communication 2004; Jonker *et al.* 2004b) similar to that seen in the last observation reported by Jonker *et al.* (2003). This is further confirmation that this source indeed returned to its lowest quiescent luminosity within several tens of days after its outburst, in contrast to the > 2 years observed so far for KS 1731–260 and MXB 1659–29.

better constrain the quiescent bolometric luminosity and X-ray spectrum of EXO 0748–676. Unfortunately, the source has remained active since it was originally discovered and no observations in quiescence have yet been possible.

2.4.2 X 1732–304 in the globular cluster Terzan 1

In 1980, *Hakucho* detected a bursting X-ray source in the direction of the globular cluster Terzan 1 (Makishima *et al.* 1981; Inoue *et al.* 1981). Several years later, a steady X-ray source was detected (X 1732–304) consistent with this globular cluster and most likely corresponding to the bursting source (Skinner *et al.* 1987; Parmar *et al.* 1989). Since then, the source has persistently been detected at 2–10 keV luminosities between a few times 10^{35} erg s $^{-1}$ and $\sim 10^{37}$ erg s $^{-1}$ (see Figure 3 of Guainazzi *et al.* 1999 and references therein) until 1999, when Guainazzi *et al.* (1999) reported an anomalous low-state for X 1732–304 during a *BeppoSAX* observation. They could only detect one dim source with a 2–10 keV luminosity of 1.9×10^{33} erg s $^{-1}$. This source luminosity and its X-ray spectrum are both very similar to those observed for the quiescent neutron star transients. This strongly indicates that X 1732–304 suddenly turned off and became quiescent after having accreted for more than 12 years. This conclusion also holds if the *BeppoSAX* source is not X 1732–304 but an unrelated source (which would likely be also part of the globular cluster; Guainazzi *et al.* 1999). The long active episode of X 1732–304 makes it a quasi-persistent X-ray transient. Wijnands *et al.* (2002a) conducted a short *Chandra* observation of Terzan 1. Although they detected one source with a 0.5–10 keV luminosity of 1.2×10^{33} erg s $^{-1}$, they could not detect X 1732–304 conclusively, with a bolometric luminosity upper limit of $1 - 2 \times 10^{33}$ erg s $^{-1}$. Based on this luminosity upper limit and a detailed examination of the accretion history of the source, Wijnands *et al.* (2002a) argued that, if this long outburst episode is typical for X 1732–304 and the source stays dormant for only decades and not centuries, then the neutron star in this source is colder than expected from the standard cooling model requiring enhanced cooling processes to be present in the core of the neutron star. The lack of a detection of the source (and thus no known bolometric quiescent luminosity) combined with the large uncertainties in its accretion history inhibit strong conclusions for this system.

2.4.3 4U 2129+47

4U 2129+47 was discovered in 1972 (Giacconi *et al.* 1972; Gursky *et al.* 1972) and, for a decade, it was seen by every X-ray instrument which pointed at it (e.g., Markert *et al.* 1979; Thorstensen *et al.* 1979; Ulmer *et al.* 1980; Brinkman *et al.* 1980; Warwick *et al.* 1981; Amnuel *et al.* 1982; Wood *et al.* 1984; Garcia 1994). In 1983 *EXOSAT* failed to detect it (Pietsch *et al.* 1983, 1986) adding 4U 2129+47 to the class of quasi-persistent X-ray transients. The source has been detected in quiescence with *ROSAT* (Garcia 1994; Garcia & Callanan 1998; Rutledge *et al.* 2000)

and recently with *Chandra* (Nowak *et al.* 2002). Its quiescent X-ray spectrum was consistent with a thermal spectrum with a power-law component. If the outburst and quiescent duration so far observed for 4U 2129+47 are typical for this source, then the luminosity and temperature observed are lower than expected from the standard cooling neutron star model (Nowak *et al.* 2002; Wijnands 2002). However, the uncertainties in the accretion history of the source hamper firm conclusions from these results. Note that all the quiescent observations were taken many years after the end of the last prolonged outburst episode of 4U 2129+47, which likely means that, if the neutron star in 4U 2129+47 behaves similar to what we have observed for the neutron stars in KS 1731–260 and MXB 1659–29, during all these observations we measure the state of the core and not of the crust since the crust has had ample time to cool down and come into thermal equilibrium with the core.

2.5 XB 1905+000

XB 1905+000 was first detected in 1974–1975 (Villa *et al.* 1976; Seward *et al.* 1976) and was consistently seen to be active for a decade afterwards (see Chevalier & Ilovaisky 1990 for a historical account until the mid-1980’s). However, no reports of activity from XB 1905+000 are available after the *EXOSAT* observations of the mid-1980’s (e.g., Chevalier & Ilovaisky 1990). Recently, we were notified (P. Jonker 2003 private communication) that the source has not been detected during a recent *Chandra/HETG* observation and it is also not seen during the *ROSAT* and *ASCA* observations presented in the public archives (A. Juett 2003, private communication). For a distance of 8 kpc, the upper limit on the source luminosity is $<8 \times 10^{32}$ ergs s $^{-1}$. These non-detections suggest that the source may have been quiescent already for over a decade, although the exact time when the source turned off remains unclear. If the neutron star in XB 1905+000 has similar properties to those of the neutron stars in KS 1731–260 and MXB 1659–29, then it is expected that the quiescent X-ray luminosity of XB 1905+000 should be dominated by the state of the core since the crust should have already returned to thermal equilibrium with the core. A further *Chandra* or *XMM-Newton* observation of this source will likely detect the source in quiescence and this will give us information about the state of the core of its neutron star. However, because the accretion history of the source is not well known, XB 1905+000 has limited usefulness in constraining the cooling neutron star models.

3 Conclusions

Observations of quasi-persistent neutron-star X-ray transients (i.e., those of KS 1731–260 and MXB 1659–29) in quiescence have demonstrated that this class of transients can be used to constrain the structure of neutron stars. However, in order to fully realize the promise of these observations, more work still needs to

be done, especially calculating cooling curves specifically for each of the neutron stars in the various quasi-persistent transients given that these curves depend on the long-term accretion history of the source which is quite different among systems.

Furthermore, additional quasi-persistent neutron-star transients should be observed and monitored in their quiescent state preferably within the first year after the end of their last accretion episode. Such observations will allow us to determine whether the behavior of KS 1731–260 and MXB 1659–29 is typical among quasi-persistent neutron-star X-ray transients. Differences might be expected not only because the accretion histories of the various sources will differ significantly from each other but also because the crusts (large heat conductivity vs. low heat conductivity) and cores (standard vs. enhanced core cooling) of the neutron stars can behave differently.

All the known persistent neutron-star LMXBs are promising candidates should they ever turn off. As shown above, several sources which were thought to be persistent have turned off suddenly, so it is possible that an additional 'persistent' source might be found instead to be a quasi-persistent X-ray transient. Unfortunately, the likelihood of any one of them turning off is low since they have now been found to be active for over 40 years (since the dawn of X-ray astronomy). More promising are those systems which have been seen to suddenly turn on in the last 20 years and which have stayed on ever since (the most promising candidates are EXO 0748–676, GS 1826–24, and XTE J1759–220). It is likely that these systems may turn off in the future and could then be used in a way similar to KS 1731–260 and MXB 1659–29 to constrain the properties of neutron stars.

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